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Soil water in relation to irrigation, water uptake and potato yield in a humid climate[☆]

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ABSTRACT

Efficiently controlling soil water content with irrigation is essential for water conservation and often improves potato yield. Volumetric soil water content (θ_v) in relation to irrigation, plant uptake, and yield in potato hills and replicated plots was studied to evaluate four water management options. Measurements of θ_v using a hammer driven probe were used to derive a θ_v index representing the relative θ_v status of replicated plots positioned along a hill slope. Time series for θ_v were determined using time domain reflectometry (TDR) probes at 5 and 15 cm depths at the center, shoulder, and furrow locations in potato hills. Sap flow was determined using flow collars in replicated field plots for four treatments: un-irrigated, sprinkler, surface drip, and sub-surface drip irrigation (40 cm depth). Irrigated yields were high/low as the θ_v index was low/high suggesting θ_v excess was a production problem in the wetter portions of the study area. The diurnal pattern of sap flow was reflected in the θ_v fluctuation it induces at hill locations with appreciable uptake. Hill locations with higher plant uptake were drier as was the case for the 5 cm (dry) depth relative to the 15 cm (wet) depth and for locations in the hill (dry) relative to the furrow (wet). The surface drip system had the lowest water use requirement because it delivers water directly to the hill locations where uptake is greatest. The sub-surface drip system wetted the hill gradually (1–2 days). Measurement of the θ_v index prior to experimental establishment could improve future experimental design for treatment comparisons.

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1. Introduction

Efficient irrigation water management provides adequate soil water for crop root uptake while optimizing irrigation water use efficiency (IWUE) and reducing losses of N and other production inputs through leaching. Precise scheduling of irrigation water applications leads to resource conservation, environmental, and production benefits (Shock et al., 2007). Drip irrigation has been shown to be a more water efficient alternative to traditional sprinkler and furrow irrigation systems for potato (*Solanum tuberosum* L.) (Waddell et al., 1999; Mohammad et al., 1999; Chawla and Narda, 2001; Yuan

et al., 2003; Onder et al., 2005; Starr et al., 2005; Wang et al., 2006, 2007; Patel and Rajput, 2007).

The efficiency with which an irrigation system uses water is in large part determined by how effectively it transmits water to the soil zones where plant root uptake occurs. For crops like potato which are grown in a hill, a uniform sprinkler application can result in a non-uniform soil wetting pattern across the hill (Saffigna et al., 1976; Stieber and Shock, 1995; Robinson, 1999; Starr et al., 2005). However, preferential wetting of the furrow (interrow) by sprinkler or furrow irrigation is wasteful because that location is characterized by high leaching and low water uptake rates by plant roots.

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When plants are small, water from sprinklers flows along the stem, increasing infiltration at the stem base (Saffigna et al., 1976). As the plant loses its erect stature, stem flow is reduced and the combination of splash and runoff from the hill sides contribute to increased infiltration in the furrow (interrow) and subsequent leaching of water and N (Saffigna et al., 1977). Drip irrigation inherently delivers water non-uniformly in the potato hill. The emitters are point sources of water, and water fans out from the emitter as a result of both matric potential gradients and gravity. The non-uniformity of initial infiltration can be ameliorated somewhat by lateral redistribution of water as matric potential gradients move water into drier areas of the hill (Stieber and Shock, 1995; Robinson, 1999). The emitters are placed on the soil surface in conventional (surface) drip irrigation (DI) or buried beneath the soil in sub-surface drip irrigation (SDI). However, drip irrigation is cumbersome in potato production because the surface drip or SDI (in the case of shallow depth of burial) lines interfere with tillage, hilling, and harvest operations. Burying the SDI drip lines below the depth of tillage may be a viable alternative for potato production, provided sufficient upward movement into the root zone can be achieved.

The measurement and analysis of volumetric soil water content (θ_v) storage and uptake patterns have been useful in evaluating and improving irrigation management practices to reduce drainage losses and increase IWUE (Green et al., 2006). Jury et al. (1976) found predictive modeling of flow and nutrient transport in irrigated potato systems highly challenging. However, diagnostic modeling techniques based on TDR measurements (Starr et al., 2005), have been recently developed to provide indicators of θ_v storage, wetting, drainage, and uptake patterns at the scale of a potato hill cross-section. These indicators prove useful for evaluating irrigation system performance by first establishing where the plant is drawing water from, then evaluating and improving the effectiveness of the irrigation system at delivering water to those locations. Uptake was modeled as a sinusoidal function fit to persistent, low amplitude fluctuations in θ_v . However, the uptake component is relatively new and warrants further evaluation. In particular, there were no direct measurements of plant transpiration (sap flow) to support the results of the uptake model.

The vast majority of literature on potato irrigation pertains to climates drier than Maine's (Bourgoin, 1984). In the cool and humid climate of Maine, about 12% of acreage under potato is irrigated (Dalton et al., 2004); however, that acreage is increasing. In this environment, potato production is hampered by both periods of soil water excess and deficit that are brought about by irregular rainfall (Benoit and Grant, 1985). Here, managing irrigation systems to alleviate water deficit stress without contributing to soil water excess is a challenge. Another complicating factor is that spatial patterns of soil water across landscapes are stable in time and the yield response to potato irrigation is dependent on the relative soil water status of a specific location (Starr, 2005). Persistent spatial patterns of soil water can have a confounding effect on statistical approaches such as analysis of variance (ANOVA) for evaluating replicated plot data in irrigation studies (Fagroud and Van Meirvenne, 2002).

The objective of this study was to evaluate water storage, uptake, infiltration, and yield patterns for four irrigation systems (SDI, DI, sprinkler, and un-irrigated) in potato hills and replicated plots under humid climatic conditions of Maine. The diagnostic indicator approach was used to quantify plant uptake patterns and water delivery timing and location for the irrigation systems. Sap flow measurements were used to study the connection between the localized uptake and plant transpiration. The persistent pattern of θ_v was characterized by deriving a soil water index that represents the underlying relative (stable) water content of the plots in the absence of treatment effects to help explain the yield response to irrigation.

2. Materials and methods

Data for the study were collected at a Newport, Maine field site operated by the USDA-ARS on a Nokomis sandy-loam (coarse-loamy, mixed, frigid, Typic Haplorthods). Plots were established in a randomized block design with four replications of the four irrigation treatments (SDI, sprinkler, DI, and un-irrigated). Field plots were 20 m long by 4 m wide (four rows of potatoes where the center two rows were used for sampling) planted with 'Russet Burbank' cultivar potatoes. Plots were arranged in a linear array with potato rows perpendicular to the slope (3.4% average slope, ranging from 1.4% at the top to 5.4% at the hill bottom) on a hillside. Each potato plot had a plot in ryegrass immediately adjacent into which potato production shifted the following year. Weed control in the plots consisted of cultivation at planting and the pre-emergence application of a mixture of herbicides consisting of Sencor and Dual (a.i. metribuzon and metolochlor, Dupont Agricultural Products, Wilmington, DE) at labeled rates. Fertilizer nitrogen was applied at the rate of 224 kg ha⁻¹ of N at planting. Pesticides were used to control insects and diseases at timing and rates commensurate with prevailing norms for the region (Olanya et al., in press).

Irrigation applications to each plot were based on tensiometer readings taken at a depth of 10–15 cm beneath the surface at the center of potato hills. Four tensiometers per irrigation treatment were placed in the field, one for each plot, and irrigation scheduling was based on an average for each treatment. Irrigation was initiated if the average reading for a given treatment exceeded 50 kPa. In the sprinkler irrigation treatment, water application ranged from 12 to 24 mm, whereas drip irrigation applications were typically 10 mm each. The SDI treatment was established by burying hard hose type drip tubing with pressure compensating emitters (Rain Bird Corporation, Tucson, AZ) to a depth of 40 cm roughly centered beneath the potato hills. For the surface drip treatment, the same tubing was placed at the top of the potato hill. The surface drip tubing was removed and replaced to allow for potato hilling operations. The sprinkler plots were irrigated with Nelson D10 spray units elevated 0.8 m and spaced at 2.4 m intervals along the center of each plot.

2.1. Volumetric water content sampling

Eight 30 cm TDR probes were installed horizontally along the direction of the potato row into the center of the root system of

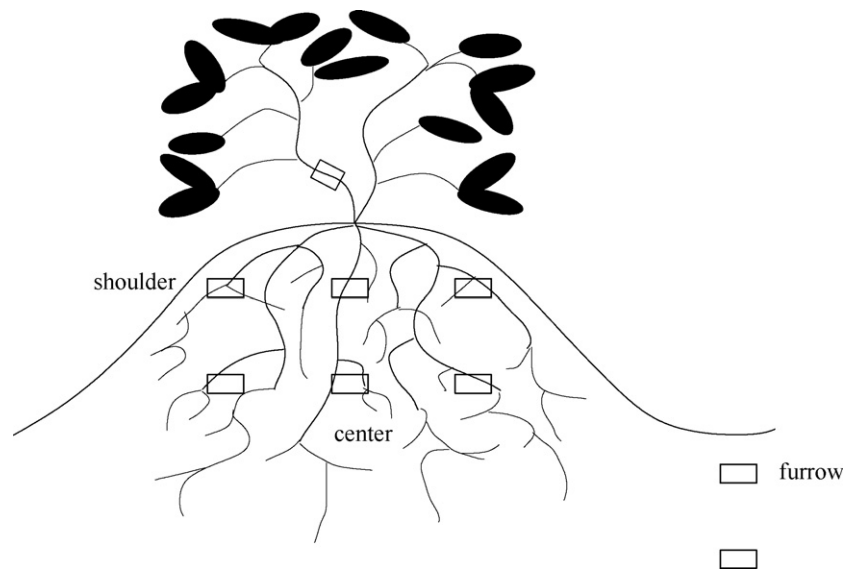


Fig. 1 – Hill cross-section showing location of θ_v and sap flow measurements.

a recently emerged plant. Soil was first excavated leaving a vertical face approximately 15 cm away from a recently emerged plant and the probes were inserted into the undisturbed plant root system at the locations shown in Fig. 1. The excavated portion of the potato hill was then reconstituted. Three sets or banks of eight probes were placed in each irrigation system, providing three repetitions of each location and system. Probes were placed at 5 and 15 cm depths for the shoulder, center, and furrow locations.

The TDR system used a TDR100 linked to a 10× data logger (Campbell Scientific, Logan, UT). A series of multiplexers was used to switch between plots and banks of probes. Each bank of eight Campbell Scientific three prong TDR probes was sampled through a Campbell Scientific SDMX50 multiplexer. Additional multiplexers were used to switch between plots and banks. The array of measurements constituted 96 probes sampled at 15-min intervals. The time required for sampling of probes was about 3 min. Sampling was done on day of year (Julian day) 221–255 in 2005 and days 188–242 in 2006. Volumetric soil water content was calculated according to Topp et al. (1980).

For the calculation of soil water index, an all terrain vehicle was outfitted with a TDR100 time domain reflectometer and associated electronics connected to a “slammer” TDR probe (Soil Moisture Equipment Corp., Santa Barbara, CA) employing a 20 cm, two prong waveguide. This apparatus was used on 10 sample dates throughout the growing season in 2006 to collect three replicate samples per plot (one on each end and one in the middle) in the ryegrass plots. The probe was inserted vertically downward from the soil surface to provide an integrated measure of θ_v from 0 to 20 cm. After averaging the three replications per plot, the data were scaled by dividing by the mean θ_v for that date to obtain the relative θ_v of each plot on each date. Then, the scaled data for each sample date were averaged over all sample dates to give the soil water index for each plot. This scaling and averaging process provides the best available estimate of the underlying stable θ_v pattern as a

function of location (Starr, 2005). Assumptions implicit in deriving the soil water index are uniform cropping and treatment within the sampling area and completion of the daily sampling before soil drying substantively biases the results.

2.2. Sap flow measurements

Sap flow gauges and a Flow32 Sap Flow System (Dynamax, Inc., Houston, TX, USA) with a total of eight microsensors (SGA10) were installed on randomly located plants within each plot. Installation was done on erect stems that had reached a maximum size (9–11 mm diameter) at 10–15 cm above the ground where stem internodes were long enough to permit a gauge. Two gauges were installed in sub-surface drip, surface drip, sprinkler, and non-irrigated plots on 28 July 2005 and 5 July 2006. The plants were checked weekly to determine if they were growing normally. If there was any indication of abnormal wilting of the collared plant, the collars were removed and relocated. The plants were destructively sampled for mass of dry leaves on the collared stem above the gauge as well as mass of dry leaves on the whole plant. During 2005, all gauges were removed and plants destructively sampled on day of year 227 and 234; in 2006, this procedure was done on 236. Sap flow (mass per unit time) was logged on a 15-min interval on a 24 h basis.

2.3. Analytical methods

Time-series data from replicated banks and symmetric probe locations were averaged to obtain a representation of the soil water dynamics at each location. Mean water storage was calculated for each location for both years of the study. The amplitude and phase of diurnal θ_v fluctuations measured with the TDR array were considered as indicators of the strength and timing of localized water uptake by roots and evaporation

(Starr et al., 2005). The time derivative of soil water content, $\delta\theta_v/\delta t$, responds to water flow to and from the measurement volume of the probe. Water uptake by roots and evaporation are gradual processes of θ_v drawdown that have a fundamental frequency of 1 cycle d^{-1} . Following averaging over replicate banks and symmetric probe locations, the fluctuations ($\delta\theta_v/\delta t$) were subjected to an amplitude limit of $0.4 m^3 m^{-3} d^{-1}$. Limiting the fluctuation amplitude in this way cuts out much of the high amplitude fluctuations associated with infiltration and electronic noise without losing information on the slow steady process of uptake. These amplitude-limited fluctuations were then averaged over every hour of each day to obtain a composite of the θ_v fluctuation daily cycle for the different years, locations, depths, and systems. The composite was thereby obtained by averaging over days 221–255 in 2005 and days 188–242 in 2006.

A sinusoidal model was used to assess these diurnal data. The model consists of a sinusoidal wave function of frequency one cycle per day plus a constant offset. The fit parameters of the sinusoidal model, in particular its amplitude and time of peak θ_v drawdown, were used to diagnose the amplitude and phase of the fluctuations. The equation

$$\frac{\delta\theta_v}{\delta t} = C + F \sin(0.262X + E) \quad (1)$$

where C ($m^3 m^{-3} d^{-1}$) is the constant offset, F ($m^3 m^{-3} d^{-1}$) the amplitude, E the phase shift, and X is the time of day in hours specifies the functional fit to experimental data. The offset represents a steady decline in water content that is typical of soil drying. The constants C , F , and E were calculated using graphing software (Grapher, Golden Software, Inc., Golden

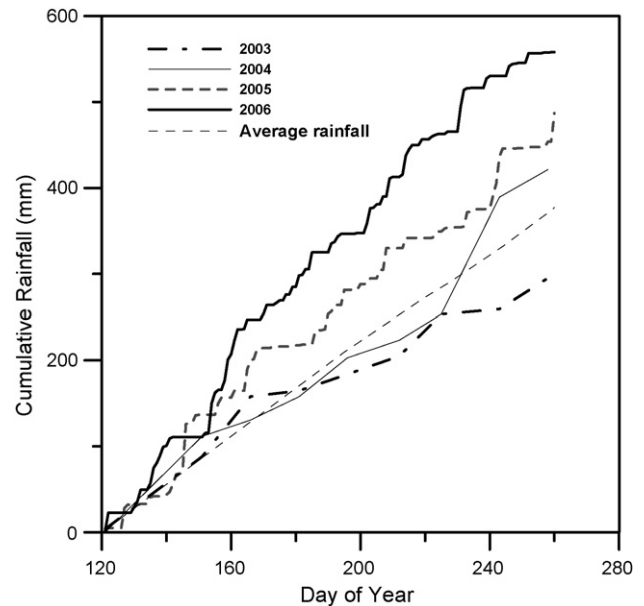


Fig. 2 – Cumulative rainfall measured at Newport, Maine field site in 2003, 2004, 2005, and 2006.

Colorado). The time of peak water uptake was calculated from the phase shift.

The sap flow data were scaled to give a measure of flow per plant using the dry weight of leaves measured at the end of each sampling interval when the collars were removed. This was accomplished by multiplying by the ratio of mass of dry leaves on the whole plant to mass of dry leaves on the stem above the collar. A sine wave function was also fit to the sap

Table 1 – Cumulative water use, yield, and irrigation water use efficiency in 2003 through 2006 as influenced by irrigation system

Year	System	Irrigation (cm)	Yield ($kg ha^{-1}$)	Mkt yield (%)	IWUE ($kg ha^{-1} cm^{-1}$)
2006	Sub-surface drip	4.5 b	26,231 a	46	2639 a
	Surface drip	3.6 a	24,998 a	45	3192 a
	Sprinkler	6.8 c	26,343 a	45	1736 b
	Un-irrigated	–	27,015 a	48	–
	LSD _{p=0.05}	0.34	6,950		573
2005	Sub-surface drip	9.7 b	23,764 a	41	1059 a
	Surface drip	6.6 a	19,729 a	36	1173 a
	Sprinkler	9.8 b	19,841 a	38	778 a
	Un-irrigated	–	18,384 a	36	–
	LSD _{p=0.05}	2.13	5,604		722
2004	Sub-surface drip	5.2 a	31,499 a	66	4114 a
	Surface drip	3.8 b	32,732 a	69	6421 b
	Sprinkler	12.3 c	32,396 a	62	1655 c
	Un-irrigated	–	30,602 a	58	–
	LSD _{p=0.05}	1.33	3,362		2120
2003	Sub-surface drip	12.2 a	31,499 a	54	1392 a
	Surface drip	11.9 a	29,594 a	59	1481 a
	Sprinkler	28.6 b	31,499 a	52	587 b
	Un-irrigated	–	29,930 a	49	–
	LSD _{p=0.05}	4.6	9,864		312

Values followed by different letters indicate significant differences ($p = 0.05$) within a given year and column.

flow data once all available data from the period of observation were averaged over every hour of each day (days 188 through 242 in 2006).

Crop yield was measured by harvesting 18 m of a potato row, washing, separating by size class, and then weighing the sample. Total yield was calculated from the weight of all potatoes, whereas marketable yields include only non-misshapen potatoes greater than 114 g in size. The IWUE values were calculated by dividing total crop yield by water applied for each plot. In all cases, statistical separation of means were determined by first conducting an ANOVA, then calculating Fisher's LSD at the $p = 0.05$ level.

3. Results and discussion

A graph of cumulative rainfall at the study site in 2003, 2004, 2005, and 2006 shows precipitation in 2004–2006 above the long-term average (Fig. 2). Although both 2005 and 2006 had periods of excessive rainfall and seasonal rainfall was very high, there were periods in July and August of both years when the soil dried in excess of 50 kPa and irrigation water was applied. Dry periods (irrigation applications) were often followed by moderate to heavy rainfall resulting in excess water. Cumulative irrigation water applied (Table 1) was low compared with cumulative rainfall (Fig. 2) in all years with the exception of the sprinkler treatment in the drier 2003 season where irrigation and rainfall were comparable.

The surface drip irrigation (DI) treatment required the least water in all years, significantly ($p = 0.05$) less than the other treatments in all but the 2003 season (Table 1). The DI also had the numerically highest IWUE (Table 1) in all years, but the differences were not as pronounced as with total water use, and IWUE for DI was only significantly higher than SDI in 2004. The sprinkler system had the numerically highest water use and lowest IWUE in all years of the study and in most cases these differences were statistically significant. The exception was 2005 when sprinkler and SDI showed no significant difference in water use or IWUE.

Irrigation treatment did not significantly impact total or marketable yield (Table 1) and the LSD was on average 24% of total yield. The variability (LSD) in yield was high compared with any expected or observed yield increase from irrigation during this period. Plots of soil water index and yield vs. distance from the top of the study slope for all irrigated treatments combined (Fig. 3a) and the un-irrigated treatment (Fig. 3b) help explain the source of some of this variability. Irrigated yield mirrored the soil water index along the hill slope. Where soil water index was high/low, irrigated yields were low/high. Soil water index was high around the mid slope and near landscape foot slope. A fifth order polynomial explained 74% of the variability in soil water index and 64% of the irrigated yield. By contrast, un-irrigated yield was only high at the lowest point on the landscape where wet, depositional soils were present. A second order polynomial fit un-irrigated yield ($R^2 = 0.99$).

The short scale variability in soil water index (Fig. 3) exhibits the type of non-random spatial structure and within block variability that can be expected to confound the analysis of yield variance (Fagroud and Van Meirvenne, 2002). Thus, it is not

surprising that we observed substantial yield differences among plots with no significant differences among treatments. Given measurements of the soil water index, it should be possible to organize experimental blocks in such a way as to “block out” this variability for improved treatment comparisons.

A plot of irrigated and un-irrigated yield vs. soil water index (Fig. 4) suggested a very different yield response to irrigation depending on the relative soil water status of a given position in the field. For the drier half of the field (soil water index less than one), un-irrigated yields were more than a standard error below the quadratic trend line of the irrigated treatment. This suggests that for the drier half of the field, irrigation may well

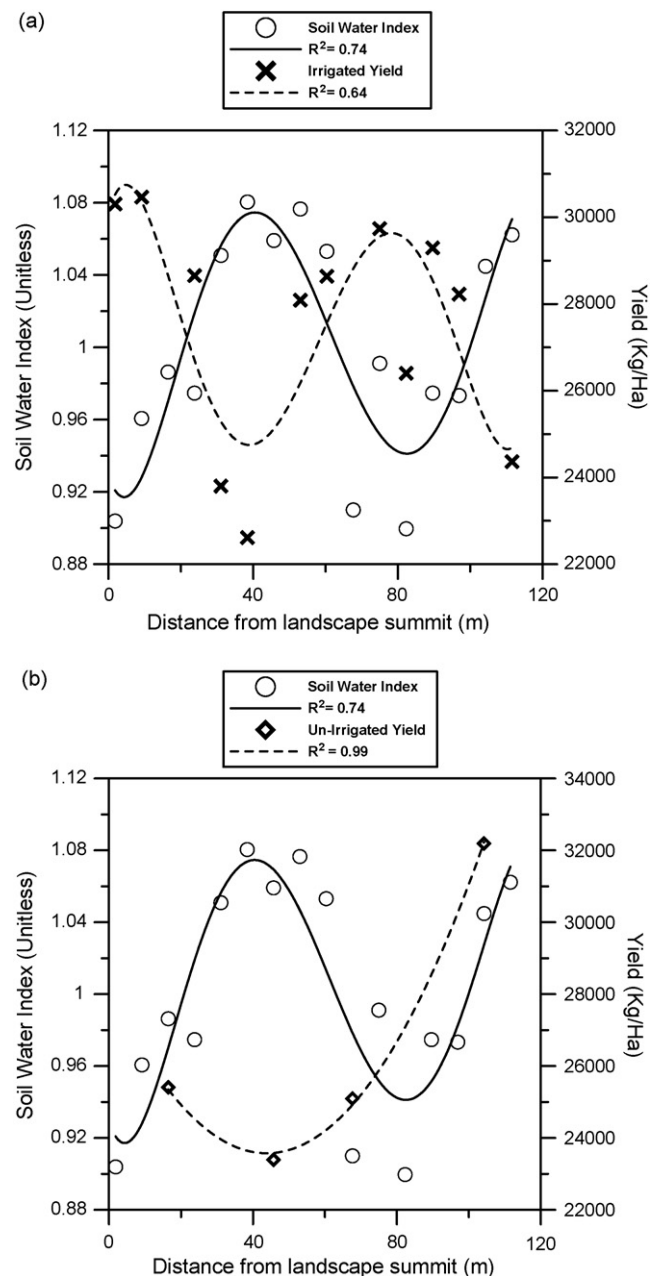


Fig. 3 – Comparison of soil water index: (a) irrigated yield and (b) un-irrigated yield as a function of distance from the landscape summit. Coefficient of determination (R^2) is calculated for the polynomial functions to fit these data.

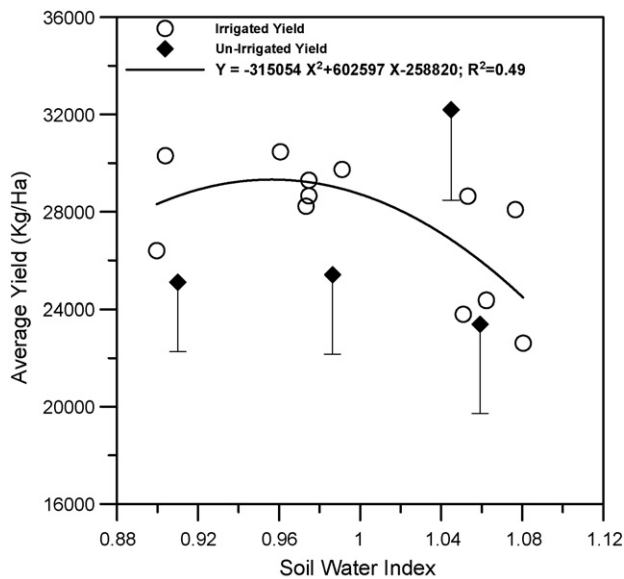


Fig. 4 – Irrigated and un-irrigated yield as a function of soil water index.

be a viable treatment even during a relatively high rainfall period such as this study encompassed. However, in the wetter half of the field, the irrigated yields declined rapidly with increasing soil water index. This suggests a problem with excess water in the wet areas, where adding more water may further exacerbate yield reductions. This observation corroborates similar field observations of negative response to irrigation in relatively wet areas in Maine (Starr, 2005). Un-irrigated yields were highly variable in the wetter half of the field, ranging from the highest observed in this experiment to quite poor. This un-irrigated yield variability manifested itself as a confounding influence on the analysis of yield variance.

The effect of potato hill position (furrow, center, or shoulder) on mean water content for the irrigation treatments was evident when data for all depths and years were averaged (Table 2). In all treatments, the furrow was significantly ($p = 0.05$) wetter than the center and shoulder locations, which were statistically identical. The separation between means was greatest in the SDI and sprinkler treatments in which the furrow was 0.1 and 0.07 $\text{m}^3 \text{m}^{-3}$, respectively, greater than the center and shoulder. These high mean values in the furrow are indicative of high drainage rates (Starr et al., 2005; Jury et al., 1976) and are linked with greater wetting of the furrow using both SDI and sprinkler. However, in the case of SDI, the point of application is below the tillage zone and irrigation water migrates upward to the hill rather than downward through the zone of agricultural chemical application. The magnitude of uptake at the various locations is a major factor in the mean water storage as will be discussed in connection with the diagnostic uptake model. The effect of depth on mean θ_v storage (Table 3) showed that soil at 5 cm was drier than at 15 cm for all treatments. The difference was statistically significant at the $p = 0.05$ level only for the three irrigated treatments. The difference in mean θ_v between 5 and 15 cm was greatest in the SDI treatment which is understandable because SDI applies water at a greater depth.

Table 2 – Effect of hill position on soil water storage for four water application treatments

Treatment	Position	Mean soil water ($\text{m}^3 \text{m}^{-3}$)
Sprinkler	Furrow	0.287 a
	Center	0.218 b
	Shoulder	0.220 b
Sub-surface drip	Furrow	0.290 a
	Center	0.194 b
	Shoulder	0.194 b
Surface drip	Furrow	0.270 a
	Center	0.222 b
	Shoulder	0.224 b
Un-irrigated	Furrow	0.268 a
	Center	0.220 b
	Shoulder	0.218 b

Letters indicate significant differences ($p = 0.05$) within a given treatment.

The 2006 daily cycle of θ_v fluctuations (an average of data for every hour of each day from day 188 through day 242) and sap flow (Fig. 5) show when, throughout the day, uptake through the plant is occurring and gives an indication of where the plant is drawing its water from. The same sinusoidal function fit sap flow (R^2 ranging from 0.66 in DI to 0.88 in un-irrigated) in 2006 as was used to model the low amplitude θ_v fluctuations (R^2 ranging from around 0.1 in the furrow to as high as 0.8 in the hill). For all irrigation systems, both the experimental data and fitted functions indicated strong uptake at all depths and positions throughout the hill, but uptake was nearly undetectable in the furrow. This low uptake at the furrow location explains the persistently high θ_v in the furrow relative to the hill. Similarly, more uptake was generally indicated at 5 cm than at 15 cm within the hill, resulting in lower θ_v at shallower depth. The temporal pattern of sap flow is reflected clearly in the fluctuating θ_v pattern, as would be expected. Only the uptake pattern for sprinkler irrigation is shown in Fig. 5. The pattern for the other irrigation systems was remarkably similar to the sprinkler system.

Because the vast majority of the uptake is indicated to be in the hill positions rather than the furrow, the efficiency with which an irrigation system delivers water to the hill will be key

Table 3 – Effect of depth on mean θ_v storage for four water application treatments

Treatment	Depth (cm)	Mean soil water ($\text{m}^3 \text{m}^{-3}$)
Sprinkler	5	0.223 a
	15	0.259 b
Sub-surface drip	5	0.206 a
	15	0.245 b
Surface drip	5	0.224 a
	15	0.245 b
Un-irrigated	5	0.229 a
	15	0.240 a

Letters indicate significant differences ($p = 0.05$) within a given treatment.

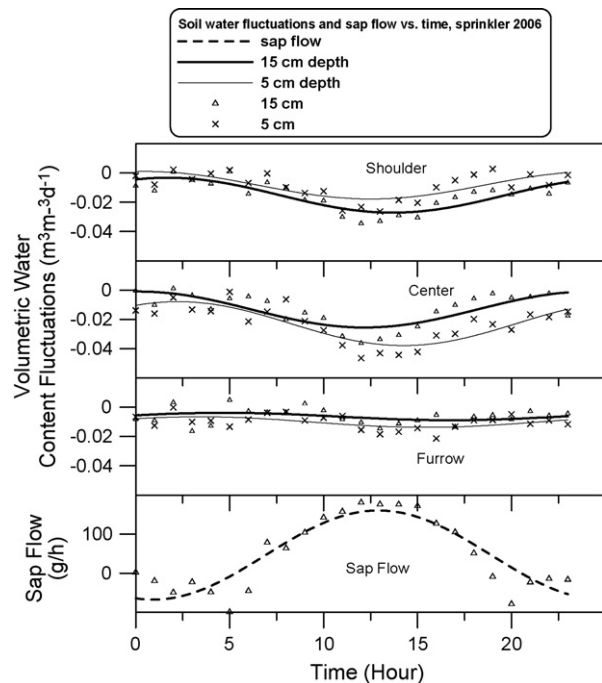


Fig. 5 – Diurnal composite of low amplitude θ_v fluctuations and sap flow under sprinkler irrigation in 2006.

to its IWUE. Conversely, more water delivered to the furrow may have less uptake efficiency. The diurnal data were averaged over all sample dates (days 221–255 in 2005 and days 188–242 in 2006) and averaged over all hill (excluding furrow) locations and depths and plotted for the 2 years of the study (Fig. 6). With the exception of the DI system in 2005 which had an unusually poor fit ($R^2 = 0.14$), the sinusoidal uptake model fit both θ_v fluctuations ($R^2 = 0.47 - 0.82$) reasonably well. Peak uptake times (Table 4) derived from the fitted functions of Fig. 6, range from hour 12.9 to hour 14.5 (again excepting DI in 2005) with no pronounced difference between irrigation systems. Uptake amplitudes (Table 4) suggest no pronounced differences between irrigation systems in their uptake amounts, although uptake did appear to be higher in the drip systems in 2005. Mean storage in the hill (Table 4) was significantly ($p = 0.05$) lower with SDI in 2006 and this could be explained by the comparatively high uptake indicated for SDI

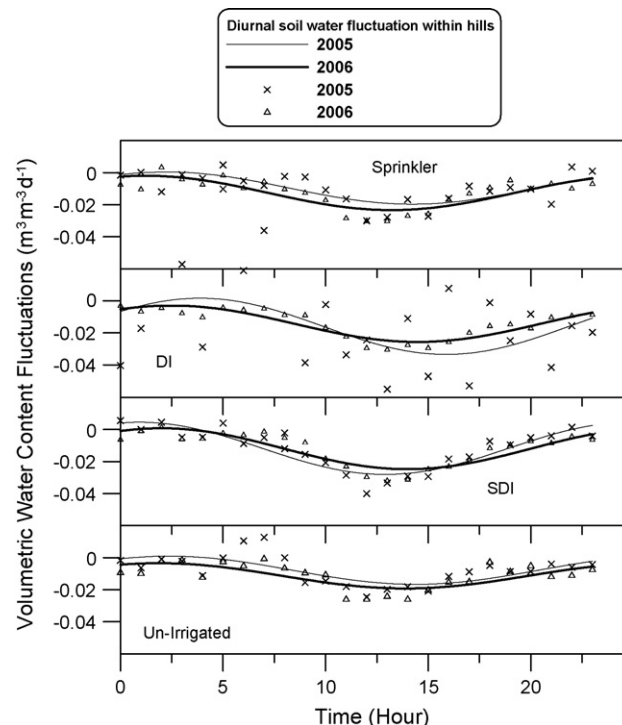


Fig. 6 – Diurnal θ_v fluctuations averaged over hill positions for four irrigation systems in 2005 and 2006 (DI: surface drip; SDI: sub-surface drip).

in the same year. Sprinkler irrigation resulted in a significantly wetter hill in 2005 when relatively low uptake was indicated and relatively more water was applied to that treatment. No significant differences were observed in furrow wetness as a result of treatment for either year. All measures indicated greater storage in 2006 than in 2005, likely the result of the greater precipitation in that year.

The θ_v response (averaged over hill locations) following an example irrigation event (Fig. 7) on day 229 of 2006 shows how the irrigation systems differ in their water delivery to the hill. Irrigation was initiated in the early morning of day 229 and the hill storage showed the most rapid response with the sprinkler system, followed by the DI system as would be expected since the DI application took nearly 2 h to complete whereas the sprinkler system required only 15 min. The SDI system, by

Table 4 – Effect of irrigation treatment on diagnostic indicators of water storage, furrow drainage, and uptake

Year	Irrigation system	Hill storage ($\text{m}^3 \text{m}^{-3}$)	Furrow storage ($\text{m}^3 \text{m}^{-3}$)	Uptake amplitude ($\text{m}^3 \text{m}^{-3} \text{d}^{-1}$)	Uptake peak (h)	R^2 uptake model
2006	SDI	0.194 b	0.289 a	0.0128	14.0	0.79
	DI	0.216 a	0.270 a	0.0113	14.5	0.82
	Sprinkler	0.219 a	0.287 a	0.0107	13.2	0.69
	Un-irrigated	0.219 a	0.268 a	0.0109	13.9	0.50
2005	SDI	0.167 b	0.249 a	0.0163	12.9	0.84
	DI	0.165 b	0.238 a	0.0175	15.9	0.14
	Sprinkler	0.202 a	0.229 a	0.0101	14.3	0.55
	Un-irrigated	0.148 b	0.227 a	0.0088	14.4	0.47

Letters indicate significant differences ($p = 0.05$) within a given year.

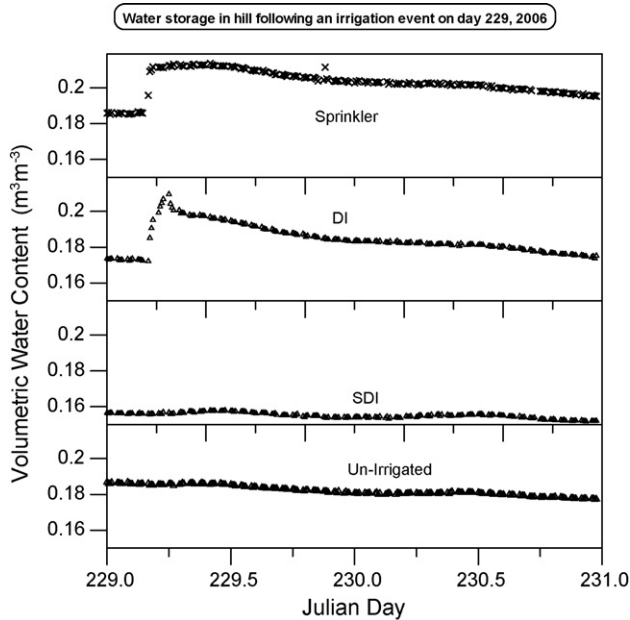


Fig. 7 – Water storage averaged over hill positions following an example irrigation event on Julian day 229, 2006 (DI: surface drip; SDI: sub-surface drip).

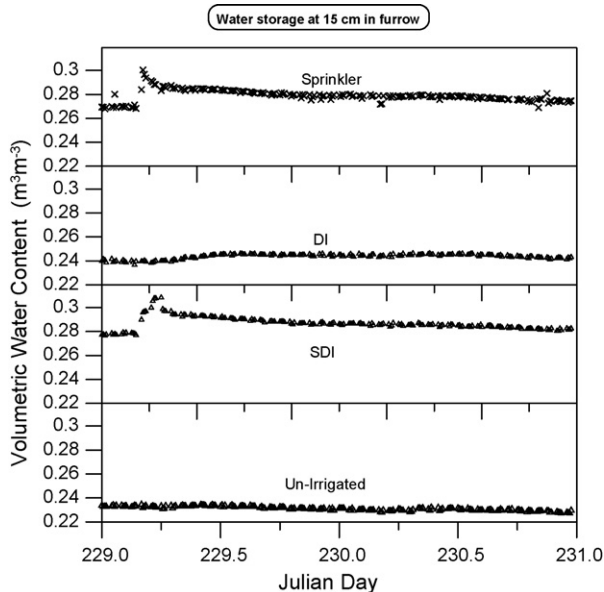


Fig. 8 – Water storage at 15 cm beneath the furrow following irrigation application on Julian day 229, 2006 (DI: surface drip; SDI: sub-surface drip).

contrast, wetted the hill only very gradually. A rise in SDI θ_v was evident at night and early morning and this extended into the following day, suggesting upward movement of water from the wetted area below the hill persisted with capillary draw being the driving force behind the upward movement.

By contrast, water delivery to the deeper location in the furrow (Fig. 8) was relatively rapid for SDI; this was not surprising given the proximity of the deep furrow probe to the

SDI emitters. The sprinkler system exhibited the most rapid furrow wetting front, whereas the DI system had a much more muted and delayed θ_v response at the furrow than either SDI or sprinkler. Water had to spread laterally around 45 cm from the DI emitters to reach the furrow location. Although lateral spreading was indicated in this way it is not a rapid way of delivering water. Thus, examination of these data reveals a consistency of observations with logical cause and effect that help explain and diagnose the systems' storage and fluxes of water. Given that the DI system delivers water directly to the soil zone where uptake is highest, that system would be expected to have the lowest water use requirement.

4. Summary and conclusions

Rainfall was above average during the 2004–2006 years and was excessive during 2005 and 2006. Inputs of irrigation water were small compared with rainfall except for the sprinkler treatment in 2003. Irrigated yield was above un-irrigated yield over the drier half of the experimental area. However, in the wetter half of the study area irrigated yield was reduced with increasing soil water. This suggests conditions of excess water were present in the wetter parts of the field that impaired irrigated production. Therefore, predictions of precipitation should be taken into account for irrigation scheduling in this humid region.

Irrigated yield depended on the soil water index ($R^2 = 0.51$) and the two parameters reflected one another when graphed vs. distance along the experimental hill slope. Un-irrigated yield was more dependent on landscape position ($R^2 = 0.99$) than on soil water index and was highest at the lowest elevation. The pattern of spatial variability in soil water index and yield suggests assumptions of spatial randomness within blocks were not valid and this confounded the yield analysis of variance. It would have been advantageous to have measured the soil water index prior to experimental establishment so that this variability could be “blocked out”. As the soil water index variable is expected to be time-stable, it may be used in that capacity for future studies.

A sinusoidal oscillation ($R^2 = 0.1 - 0.9$) was evident at the shoulder and center locations under all water management systems at both the 5 cm and 15 cm depths of sampling. However, diurnal fluctuation was virtually undetectable at both depths of the furrow location. The model indicated that uptake was substantial throughout the hill, but not the furrow, and this may be directly linked with the significantly greater wetness of the furrow relative to the hill locations (center and shoulder). Similarly, greater uptake amplitude was indicated at 5 cm depth than at 15 cm, and this coincides with a significantly drier soil at 5 cm than at 15 cm. Treatment differences on season average water indicators were muted in this study because of the high level of water inputs from rainfall relative to irrigation water application.

The water management treatments did show substantial differences in their wetting of the hill and furrow following irrigation. Sprinkler exhibited a rapid wetting of both hill and furrow. The DI system rapidly wet the hill, but only gradually wet the furrow. The SDI treatment showed a very slow wetting of the hill, but a rapid wetting of the furrow. The DI system

delivered water directly to the zone of soil uptake in the hill and this was responsible for its relatively low water use requirement and high IWUE.

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